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PHYSICS AND TECHNIQUES OF REMOTE SENSING FOR WEATHER AND CLIMATE RESEARCH

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Space based remote sensing techniques during the last three decades have made important contributions to the understanding of our planet earth. Visible, infrared and microwave regions have been used extensively for the remote sensing of the atmospheric and oceanographic parameters needed for weather and climate research. Microwave sensors due to their ability to propagate through the atmosphere without being influenced very much have drawn the attention of oceanographic community in particular and atmospheric scientists in general for providing quantitative information. This paper deals with research primarily carried out by Indian scientists using microwaves, both passive and active, to study our planet earth together with satellite system planned for future and various international programs whose data would be useful for studies of monsoon.

Key Words: Remote Sensing; Weather; Climate; Visible; Infrared and Microwave Regions

Introduction

Three decades of satellite observations of the earth have provided much information of the different phenomena and over the years the need to understand the earth as a system has developed. NASA has already planned 'Mission to Planet Earth' and space agencies of Japan and Europe have joined them in the overall effort of monitoring the earth as a system. In India, the launch of INSAT series of satellites for weather monitoring, IRS series for earth resources applications and some of the earlier satellites such as Bhaskara for oceanographic applications, have changed the perspectives of both the scientists and the informed public regarding weather prediction and natural resources management.

Mathematical models are the basic tools for prediction which can simulate, describe and predict natural processes. These models require input data and time series of global observations from space with selected simultaneous *in situ* observations are indispensable for the models to become reliable. Observations are also needed to simplify and parametrise the complex physical processes so that they can be incorporated into models. Observations over the atmosphere and oceans are important. The observations over the oceans are very sparse and there appears to be no immediate prospects of improving it by conventional *in situ* observations. Under the above circumstances, the data from satellites are all the more necessary. For the study of regional phenomena such as monsoon in the Indian context, whose lucid description is given by Das, P K [1] and whose origin is believed to be in the oceans, we must monitor weather parameters over the oceans. The spectral peak of the incident solar

radiation arriving at the earth is in the visible part of the spectrum, where atmosphere is relatively transparent. So over the major oceanic portion of the globe that part of the energy (~ 70%) that is not reflected directly back to space, is absorbed not by the atmosphere but by the upper few ten of meters of the sea. The major currents redistribute this amount of heat around the oceans, and subsequent release of heat to the atmosphere drives the atmospheric circulation. Ocean's role in climate studies is mainly represented by the large exchange of energy at the interface through air-sea fluxes, heat absorption and redistribution by ocean currents and gyres. Coupled ocean-atmosphere models are under development for global and regional scale studies.

Microwave sensors have the unique advantage of providing all weather data over oceans. It is always advantageous to use data from sensors operating at different wavelengths so that optimum advantage can be taken from each sensor. Certain ocean parameters such as wave height and ocean wave spectrum are unique to microwaves. Data obtained from our own satellites and satellites from the other countries have given us the opportunities to learn the physical basis of measurements and the retrieval algorithms to enable us to compare the geophysical variables obtained from satellites and *in situ* observations. In this review article, some examples will be given about the scientific results obtained using primarily passive and active microwave sensors. These experiences which have been gained will be useful to plan our own ocean/atmospheric earth observing mission and collaborate with scientists in other countries.

Physical Basis of Passive Microwave Radiometry

Microwave radiometry is the detection of natural thermal radiation. The propagation of electromagnetic radiation through the earth's atmosphere where it encounters absorption, scattering and thermal emission, is described by radiative transfer[1a]. The upwelling radiance in a monochromatic spectral band at the top of the atmosphere, can be written as

$$I_\nu(p=0)=\varepsilon_\nu B_\nu(T_s)\tau_\nu(p_s\to 0)+\int_{p_s}^{0} B_\nu[T(p)] \times\frac{\partial\tau_\nu(p\to 0)}{\partial p}\,\mathrm{d}p+(1-\varepsilon_\nu)\tau_\nu(p_s\to 0) \times\int_0^{p_s} B_\nu[T(p)]\frac{\partial\tau_\nu(p\to p_s)}{\partial p}\,\mathrm{d}p, \qquad \ldots(1)$$

where $\tau_\nu(p_i\to p_j)$ denote the transmittance functions. The pointing direction of the arrow indicates the direction of the atmospheric emission (e.g. $\tau(p_s\to 0)$ means transmittance from surface to space).

$\varepsilon_\nu B_\nu(T_s)$ = upwelling radiance at the surface
T_s = surface temperature
ε_ν = emissivity of the surface

$$\frac{\partial \tau_i}{\partial p}(p_i \rightarrow p_j) \quad = \text{weighting function}$$

Eq. (1) is the fundamental equation describing the upwelling radiation at the top of the atmosphere. The first term denotes the surface contribution. Term 2 represents the direct atmospheric emission. As the atmosphere (to a first approximation) is radiating isotropically, it is not the only direct emission that contributes to the signal at the top of the atmosphere, that part of the emission which is reflected back by the earth's surface at the same frequency (term 3) has also to be taken account.

Obviously the observed radiance reflects the gaseous profiles, temperature and surface effects, so in principle it should be possible to derive the latter by inverting eq. (1). Eq. (1) looks slightly different in IR and microwave parts of the spectrum. In IR, the surface emissivity is taken as unity, therefore term 3 disappears in eq. (1). In the microwave region (1mm to 1m), the surface emissivity varies over a wide range, 0.4 to 1.0. Consequently term 3 cannot be neglected in this region. However, in the microwave region, Planck's function is linearly related to temperature and this is referred to as Rayleigh Jeans (RJ) approximation. Because of this reason, we use temperature for radiative transfer eq. (1). Using RJ approximation for a blackbody gives

$$B_\nu(T) = \frac{2kT}{\lambda^2}. \qquad \ldots (2)$$

The RJ approximation for a blackbody. However, radiation from a gray body, for a given wavelength, is equivalent to radiation from a blackbody at lower temperature. This temperature is referred to as the brightness temperature T_B of the gray body. Thus

$$T_B = \varepsilon T \qquad \ldots (3)$$

Consequently eq. (1) becomes under RJ approximation as

$$T_B(0) = \varepsilon_\nu T_s \tau_\nu(p_s \rightarrow 0) + \int_{p_s}^{0} T(p) \frac{\partial \tau_\nu}{\partial p}(p \rightarrow 0)\, dp + (1 - \varepsilon_\nu) \tau_\nu(p_s \rightarrow 0) \int_{0}^{p_s} T(p) \times \frac{\partial \tau_\nu(p \rightarrow p_s)}{\partial p} dp \qquad \ldots (4)$$

The emission from ocean surface under different wind conditions and for frequencies below 40 GHz, generally used for surface remote sensing is given by Pandey and Kakar[2]. The absorption, emission and transmission properties of the atmosphere are mainly due to the following effects.

—oxygen molecule
—water vapour molecules
—absorption and scattering by water droplets

The frequency dependence of these effects are known to useful extents[3] and microwave radiometry has been used for quantitative measurements of

water vapour content and liquid water contents[4,5]. Oxygen, a major constituent of the atmosphere has a relative volume abundance of 0.21 whereas CO_2 which is a minor constituent has a relative volume abundance of 0.003. The measurements of microwave radiation at different frequencies with different oxygen absorption can be used for atmospheric temperature retrievals as is done with MSU instrument of the TIROS Operational Vertical Sounder (TOVS)[6,7]. Fig. 1 shows the microwave spectrum and the absorption lines selected for planned Advanced Moisture Sounder (AMSU).

Parameter Retrieval

The general scheme for parameter retrieval is shown in Fig. 2. The models of the atmospheric molecules, water vapour, oxygen and clouds, models of the ocean and ice are used to calculate emissivity, absorptivity and transmissivity which are then integrated by radiative transfer model to produce brightness temperatures, for a given frequency, polarisation and incidence angle. If antenna pattern effects are negligible, then brightness temperature approximates the antenna temperature. The most used retrieval methods are the one termed as Statistical retrieval methods and have been used for retrieving several meteorological and oceanographic parameters. The subject of retrievals has received considerable attention in recent years due to requirements of quantitative information for numerical models[8].

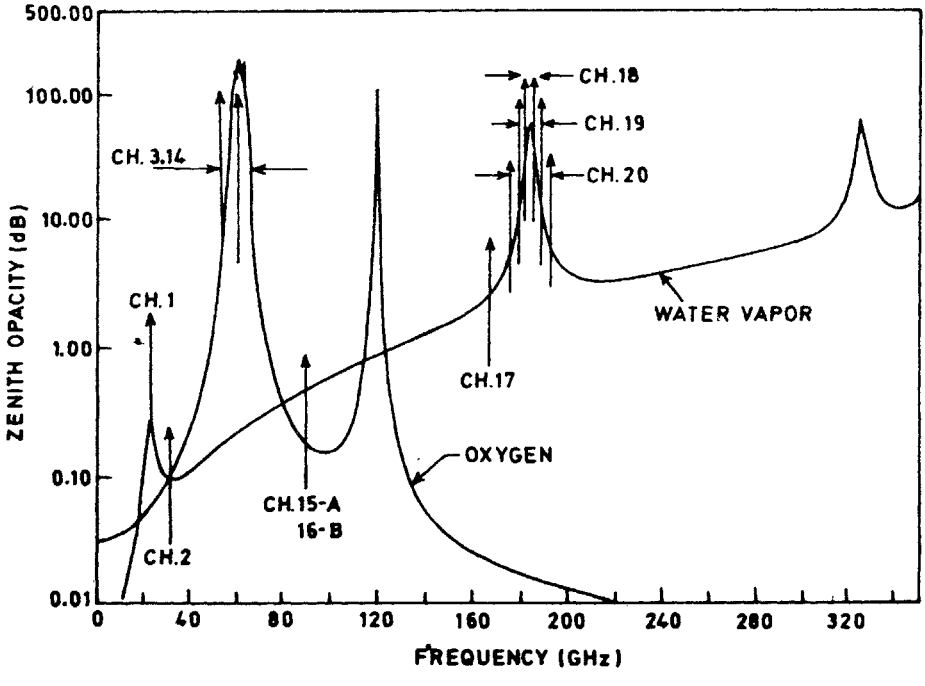

Fig 1 Atmospheric absorption lines and AMSU channels

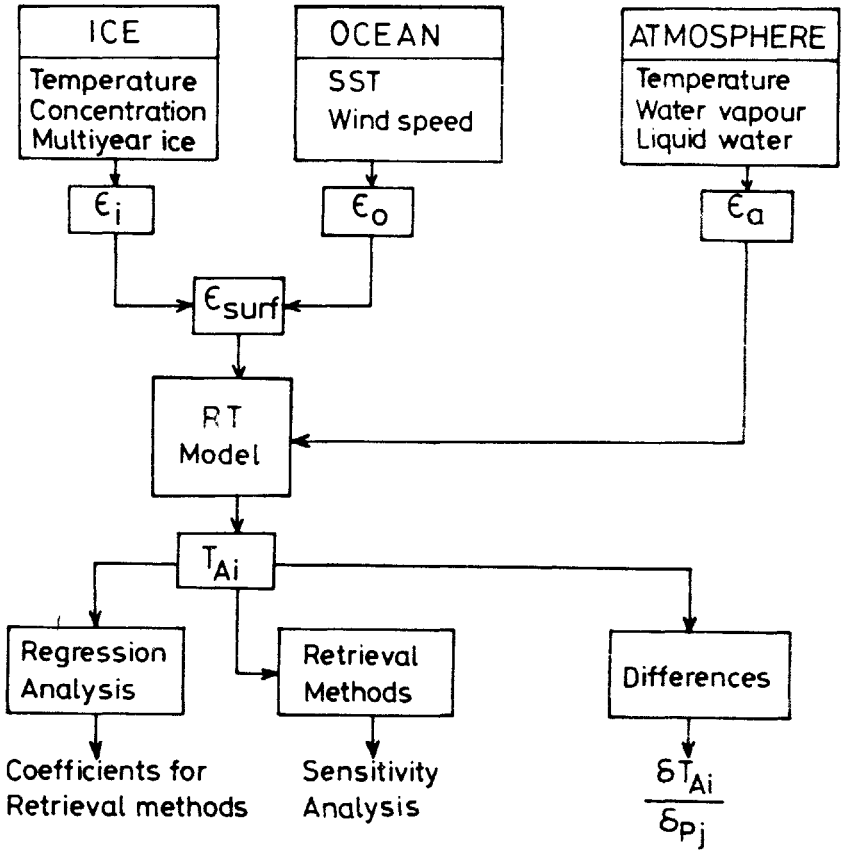

Fig 2 Context diagram showing the major components of radiative transfer computation and parameter retrieval

Some Examples of Scientific Results

Precipitable Water

The total atmospheric precipitable water over the oceanic regions has been studied extensively using passive microwave radiometer data. The satellite Microwave Radiometers (SAMIR) on board the Indian Satellites Bhaskara-I and II, have been used to derive precipitable water over the seas around India and its latitudinal variations[4,9]. The study was further extended by Gairola *et al.*[5] to compare SAMIR products with NOAA derived precipitable water. The study demonstrated the usefulness of all weather availability of moisture data over oceans and its application to map moisture field in a developing cyclone. The retrieval accuracy of total precipitable water with Bhaskara was comparable to that obtained from the previous similar missions[10].

The launch of SEASAT and NIMBUS-7 satellites by NASA with ten channels radiometer operating at 6.6, 10, 18, 21 and 37GHz with dual polarisations, have given global observations. The validation of precipitable water

with *in situ* observations have given an rms error of 0.2-0.4gm/cm^2. A new algorithm was developed to retrieve various geophysical parameters[11] from multichannel observations. Fig. 3 gives the validation curve, and Fig. 4 gives the global distribution of moisture field[12] obtained using SEASAT-SMMR (Scanning Multi Channel Microwave Radiometer data). Cloud liquid water contents were also retrieved from these measurements, but they were not validated due to non-availability of frequent *in situ* measurements as in the case of humidity profiles.

Latent Heat Flux Study over Oceans

The total precipitable water derived from SEASAT-SMMR and the recent satellite DMSP (Defense Meteorological Satellite Program) of U.S.A. with SSM/I (Special Sensor Microwave Imager) giving the total precipitable water has been used by Gairola *et al.*[13,14], Gautam *et al.*[15], 1993 and Nimmi *et al.*[16] for the study of latent heat flux over Indian oceans. They modeled the surface level air humidity, a parameter required for flux calculations using Bulk Aerodynamic formultions, in terms of satellite derived product derived product of

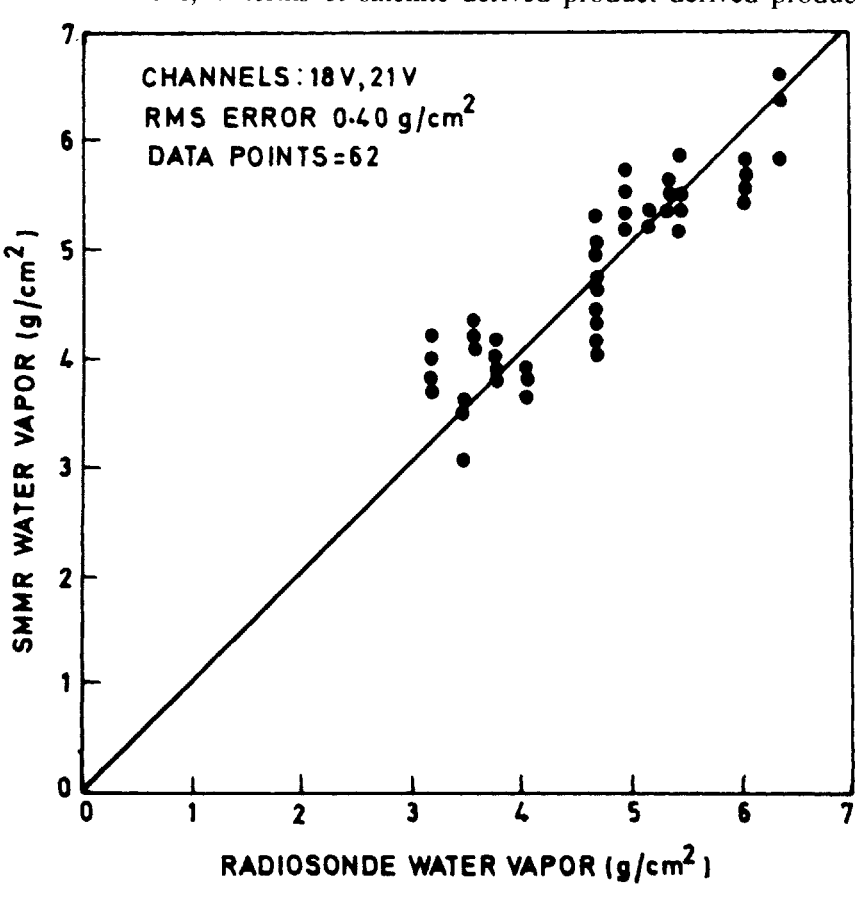

Fig 3 Comparison of precipitable water derived from SEASAT SMMR and nearby radiosonde for the month of September 1978 (after Pandey 1992)[12]

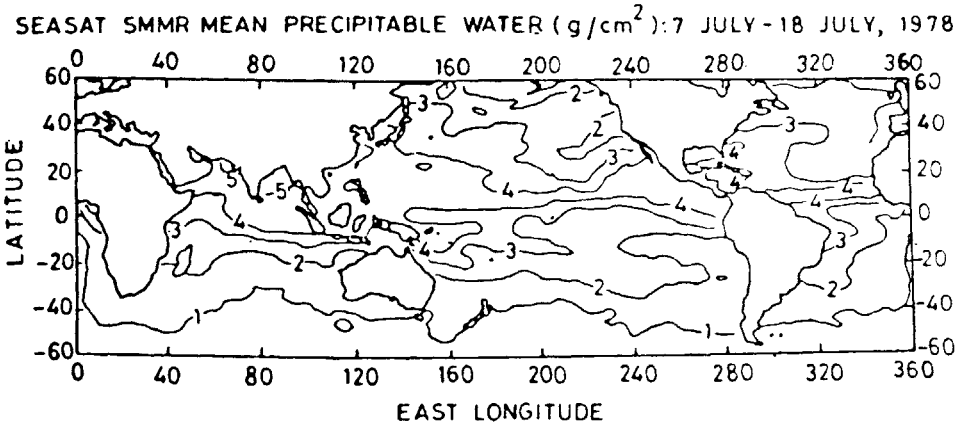

Fig 4 Global SMMR moisture field for the period July 7-July 18, 1978 (after Pandey 1992)[12]

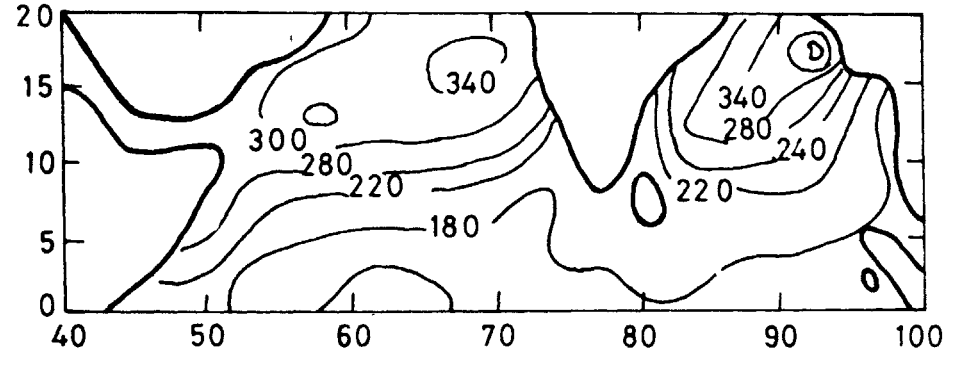

Fig 5 Latent heat flux (W/m^2) distribution for January 1988 from SSM/I and NOAA-AVHRR data over Indian oceans. (after Nimmi Nair *et al.* 1993)[16]

precipitable water. Liu *et al.*[17] had already demonstrated this type of approach for global computation of latent heat fluxes. These studies demonstrated the usefulness of passive microwave radiometry for air sea interaction study along with other satellite derived products such as SST from NOAA-AVHRR, and wind speed from either a scatterometer or passive radiometer. Fig. 5 gives a typical distribution of latent heat fluxes over Indian ocean. The accuracy of satellite derived fluxes with direct flux calculations using ships' observations gave an rms error of ~ 60 Watts/cm^2 using instantaneous observations. On monthly scales the accuracy of ~ 30 Watts/m^2 have been reported[18]. Simon and Joshi[19] studied air-sea interaction associated with a tropical cyclone using NOAA and GEOSAT data. In the absence of any direct observations over the oceans for such types of studies, satellites are going to play major roles in the future.

Kishtwal *et al.*[20] have also used satellite information to study surface level moisture transport during southwest monsoon. They have used NOAA/HIRS data for their study. Their analysis indicated a net positive surface level mois-

ture flux divergence and negative surface level moisture flux divergence over the Bay of Bengal. Fig. 6 gives an example from Kishtwal *et al.*[20] Water vapour periodicities over Indian ocean during contrasting monsoons were also studied using NOAA satellite data by Kishtwal *et al.*[21] Efforts are underway to use satellite derived precipitable water alongwith characterization of the atmosphere from the past historical data to obtain humidity profile over oceans which forms important inputs to Numerical Weather Prediction Models.

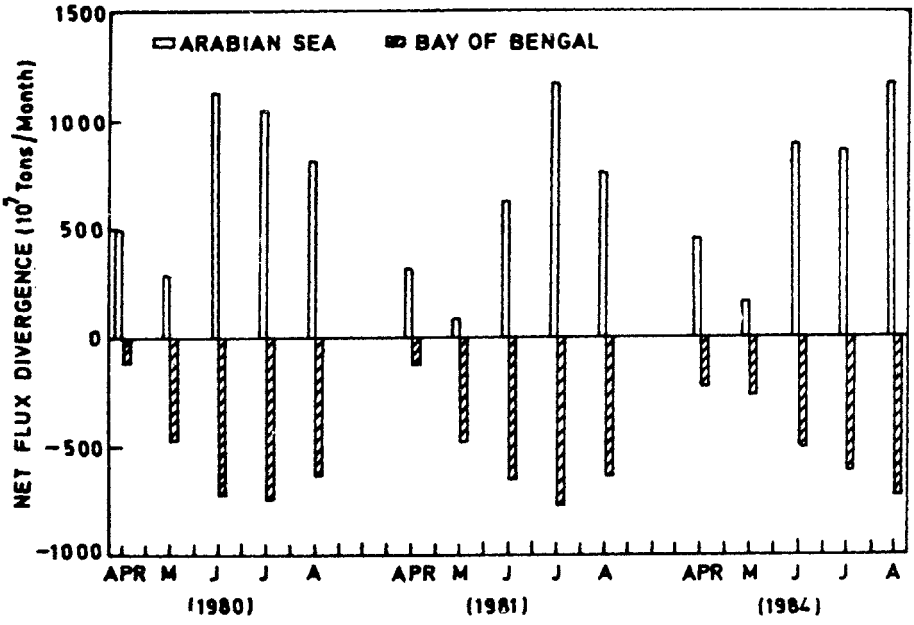

Fig 6 Flux divergence over the Arabian Sea and Bay of Bengal using NOAA HIRS data. (after Kishtwal *et al.* 1993)[21]

Wind Speed

Oceanic wind speeds are obtained from passive microwave sensors, scatterometers and radar altimeters. In case of passive radiometry, wind speeds are derived using multichannel observations since emissivity of ocean surface are wind speed dependent, in addition to wavelength, polarisation and observation angle. Fig. 7 shows the comparison of wind speed derived from SEASAT-SMMR with ships observations over North Atlantic during a special campaign, JASIN (Joint Air-Sea Interaction). The comparison gave an rms accuracy of 1.5m/sec[22].

SEASAT Scatterometer which was an active sensor operating at 14.6 GHz provided backscattering measurements at HH polarisation, which has been used to retrieve oceanic wind vector-speed and direction. Bragg scattering mechanism has been used to explain the radar return. The details of the instruments are described by Brown *et al.*[23]

Since the dependence of σhh^{o} on ocean parameters are not fully understood, an empirical model function approach has been used to define the dependence

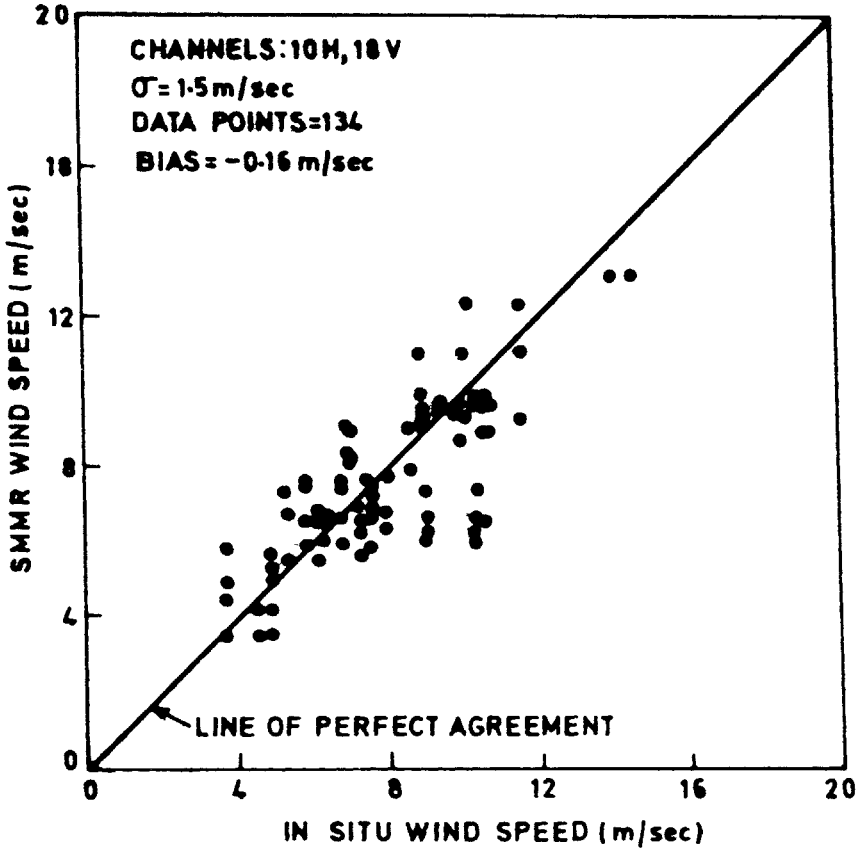

Fig 7 Comparison of wind speed derived from SEASAT SMMR data and its comparison with *in situ* observations during JASIN Experiments (after Pandey 1987)[22]

of σ^0 on windspeed incidence angle and azimuth angle. Due to harmonic nature of dependence, multiple solutions are obtained which satisfy the measurements, posing a challenge to determine the unique solution. Gohil and Pandey[24] gave an algorithm for wind vector retrieval from two beam configuration such as SEASAT-SASS. The problem of ambiguity removal was minimised by making three measurements for a pixel such as in ERS-1 scatterometer operating at 5.3 GHz. Gohil[25] gave a median filter approach to remove the wind ambiguity and did simulations using three beam ERS-1 scatterometer configuration. He used the model function provided by ESA and which is different than the model function generated for SEASAT. Fig. 8 describes some simulation results from Gohil[25]. Sarkar and Raj Kumar[26] gave a new semiempirical sea spectrum for estimating the scattering coefficients which was later related with ocean surface wind.

Radar altimeter is another quantitative instrument to provide wind speed along a narrow swath below the satellite. Due to limited coverage, these measurements are useful for climatic studies. Gairola and Pandey[27] investigated the effect of foam and white caps on extraction of wind speed from pulse limited

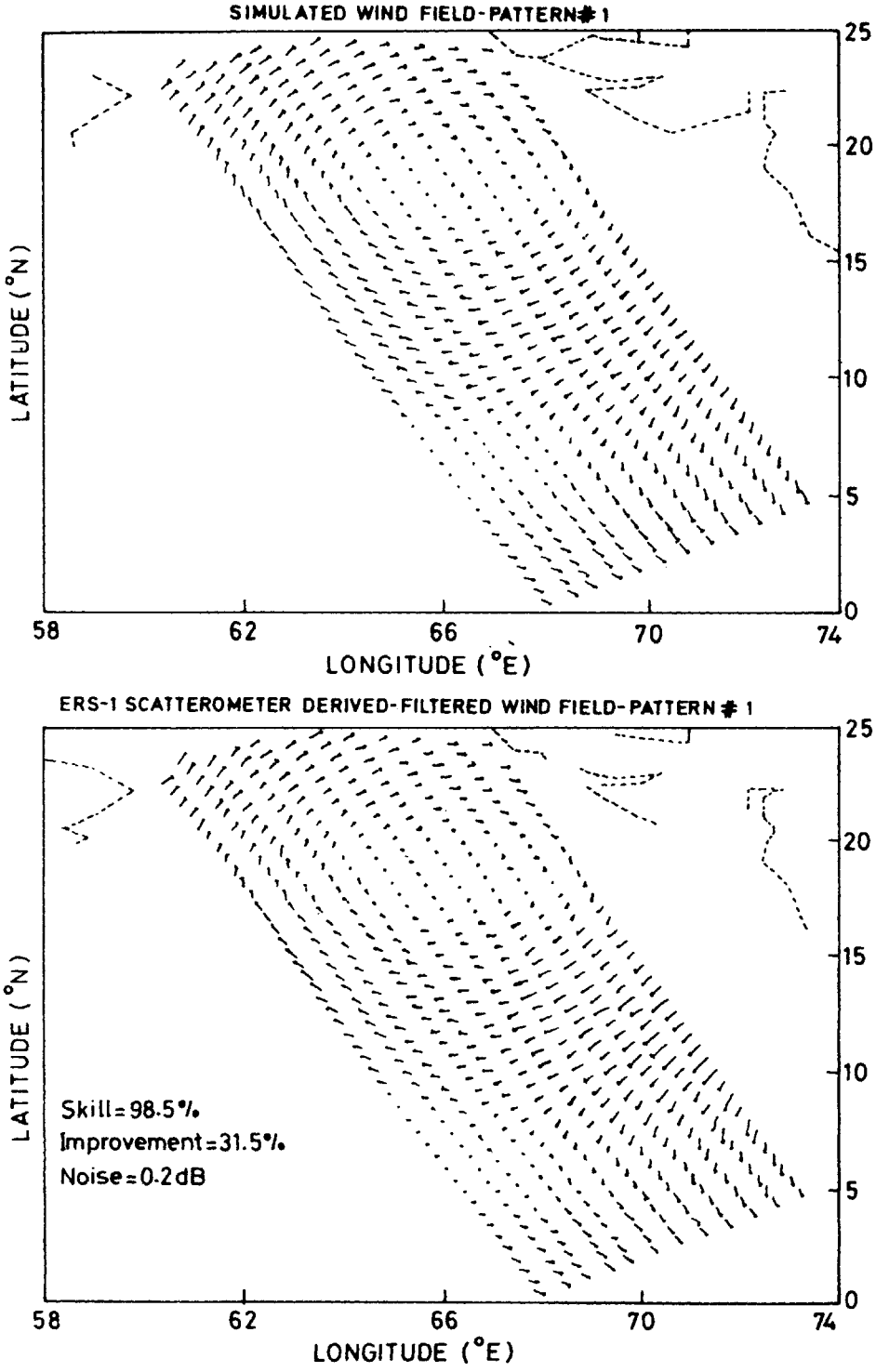

Fig 8 ERS-1 simulated results for wind vector retrieval (after Gohil 1992)[25]

radar altimeter data. Pandey[22] compared the wind speed obtained from SEASAT Scatterometer, radar altimeter and microwave radiometers. They found very interesting discrepancy and similarity which were not independent of location. Through such intercomparisons, basic questions about the physical processes responsible for the signal at the satellite and the calibration of the instruments were brought out. Woiceshyn[27] later on also noted similar discrepancy in extreme wind conditions between SASS winds and *in situ* or from pressure fields.

In addition to microwaves, which are very unique in terms of providing wind speed and wind vector, Bhandari *et al.*[28] used INSAT-VHRR images successfully to obtain wind speed from sunglint pattern of the image. Although wind speed derived from sunglint studies are limited in scope in comparison with Scatterometer and radiometers due to limited spatial coverage, nevertheless they provide an alternative "*in situ*" measurement of wind speed to compare with microwave measurements such as from sensors on board ERS-1.

Precipitation Measurements

Recently Gairola and Krishnamurthy[14] gave an algorithm for evaluating rain fall rate over oceans from a mix of satellite and surface based observations. The component of the data sets used were the outgoing Long Wave Radiation, microwave radiometric data from the special sensor microwave imager (SSM/I) and the surface rain gauge data. The method proposed by Gairola and Krishnamurty[14] assimilates these three data sets to provide improved field of global tropical rainfall. The methods are being used for initialisation of the global numerical weather prediction models and Krishnamurty's Group has noted the large impact. Similar effort is underway with Space Applications Centre and NCMRWF, Delhi.

Prior to the application of hybrid approach mentioned above, Bhandari *et al.*[29] studied precipitation measurements from INSAT images and its comparison with coastal radar at Madras in collaboration with IMD

Sea Surface Temperature

The sea surface temperature from satellite platforms are obtained from both using thermal infrared channels and microwave channels. The 3.7, 11 and 12μm channels in the infrared have been used on board TIROS-N series of operational polar orbiting weather satellites to continuously monitor global sea surface temperature for cloud free regions. The sensor is called AVHRR (Advanced Very High Resolution Radiometer) and is a five channel imaging device whose visible channels are used for cloud filtering. The two visible channels have also been used for global vegetation monitoring in terms of Normalised Difference Vegetation Index (NDVI). The next generation of AVHRR planned to be introduced in the near future will have a channel at 1.6μm which will be switchable with 3.7μm channel. This new channel will be useful for day time operation and will provide better measurements of marine aerosols. An improved configuration for SST measurements is provided by ATSR/M (Along Track Scanning Radiometer-Microwave) from ERS-1 satellite. It is expected

that ATSR, which provides multiangle and multichannel measurements will provide a two fold improvement in accuracy. These sensors are providing SST to an accuracy of .5 to 1K under different conditions[30,31]. In the tropics, the problem of water vapour reduces the accuracy of SST measurements. Moreover, the single channel observations such as INSAT-VHRR are of limited use for quantitative SST determination[32].

The history of SST measurements using microwave sensors from space platform are new in comparison with IR sensors which has a long history. The SEASAT and NIMBUS-7 satellites carried a ten channel microwave radiometer whose 6.6 GHz channels have been used for sst determination, alongwith other channels for atmospheric correction[33,34]. The accuracy with these experimental satellites are 1 to 1.5 K, but under cloudy conditions also where IR measurements are not available. Much of these errors could result from the method of comparison, skin temperature versus bulk temperature, spatial average versus point measurements, lack of true coincidence etc. Moreover, the footprint size of microwave channels are quite large, (~ 150km for seasat) in comparison with IR (2-1km). Thus microwave measurements are suitable for large scale applications and are complimentary to IR measurements. Fig. 9 gives global SST obtained from SEASAT SMMR data.

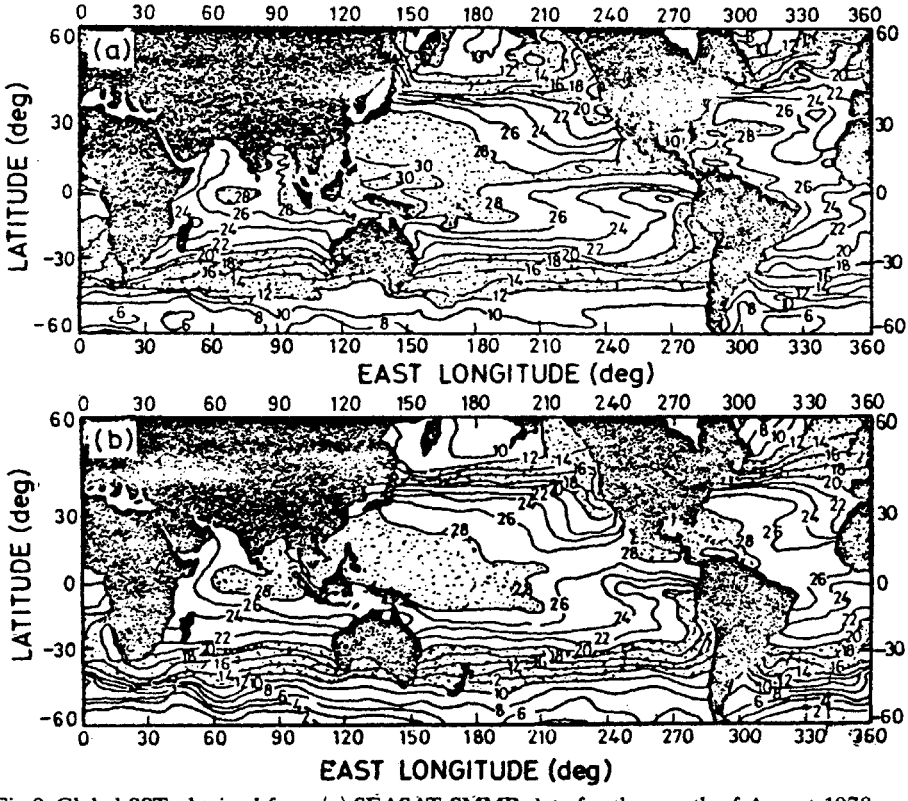

Fig 9 Global SST obtained from (a) SEASAT SMMR data for the month of August 1978 and (b) Climatological SST map for August 1978 (after Pandey and Njoku, 1982, *JPL, Private Commun*)

It is often departure from the mean SST distribution that is important rather than the distribution itself, and one of the most significant short term climatic fluctuations is also with anomalous distribution of SST in the tropical Pacific Ocean. This is El-Nino Southern Oscillation which occurs every few years and persists for about a year.

Other Studies with Satellite Data

Other interesting studies have been carried out to optimise sensors and improve the data analysis techniques[2]. In one of the applications of altimeters da-

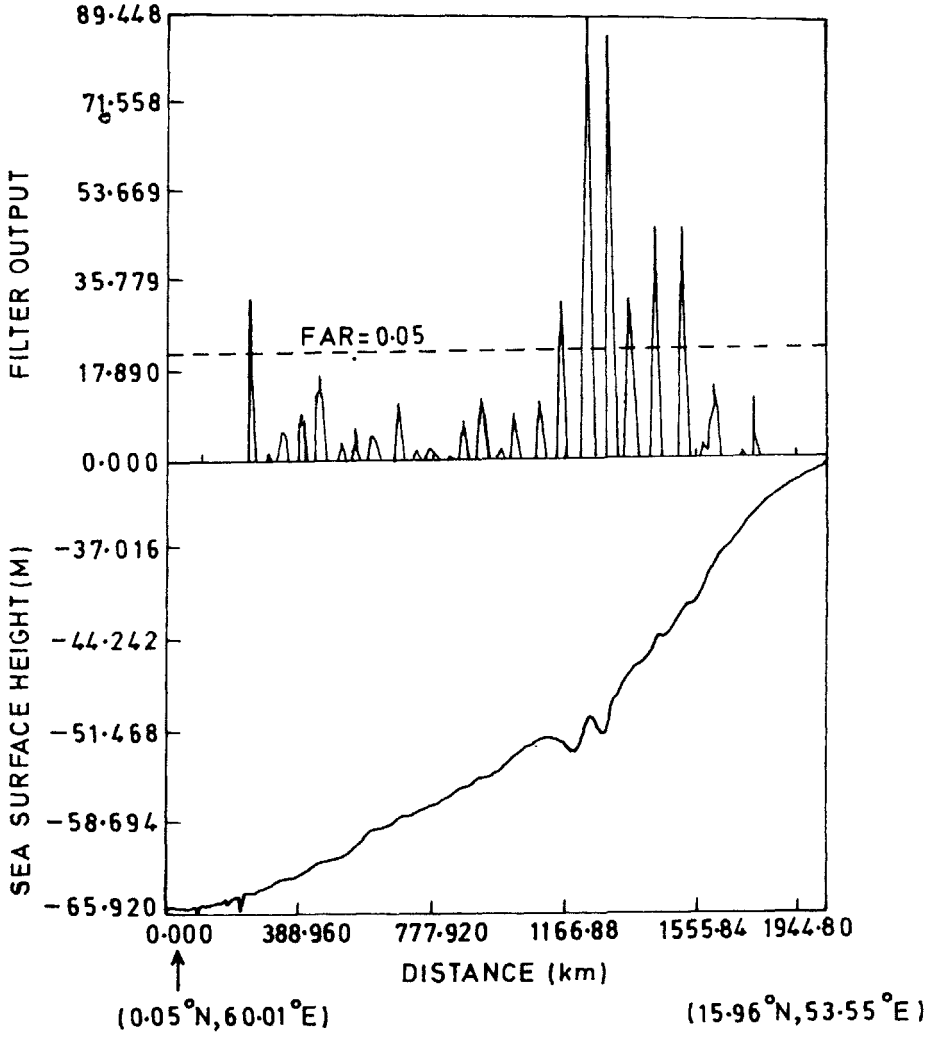

Fig 10 Detection of error seamount in the collinear track from GEOSAT Altimeter data (after Basu *et al.* 1990)[35]

ta, Basu *et al.*[35] developed the matched filtering technique to detect seamounts over the Arabian sea, Bay of Bengal, and the Indian oceans using GEOSAT altimeter data. The filter was designed using typical models for the geoid undulation signature of a sea mount and power spectral density of the background noise. The efficiency of the matched filtering technique was tested by introducing a virtual sea mount signature in the background noise. The output of the filter faithfully located the virtual seamount signature. The technique was also validated by precisely locating the charted seamounts like Somali Ridge and Error seamounts in the Arabian sea. Several new sea mounts were also predicted. These studies have found applications in Geology and fisheries, in addition to other oceanographic applications. An example of sea mount detection is given from Basu *et al.*[35] Basu and Pandey[36], did numerical experiments with modeled return echo of a satellite altimeter from a rough ocean surface and a simple iterative algorithm for the estimation of significant wave height was developed.

International Efforts

Several international programs for the study of oceans, atmosphere and hydrology have been launched in recent years, some of them are ongoing and others are at different stages of planning. The objective of listing some of these programs is to encourage scientists to direct their research keeping in mind the ongoing international large scale programs.

1. World Climate Research Programme (WCRP)
2. Tropical Oceans and Global Programme (TOGA)
3. World Ocean Circulation Experiments (WOCE)
4. International Hydrology Programme (IHP)
5. Global Energy and Water Cycle Experiments (GEWEX)
6. Joint Global Ocean Flux Study (JGOFS)
7. International Satellite Cloud Climatology Projects (ISCCP)
8. International Global Atmospheric Chemistry Programme (IGAC)
9. International Geosphere-Biosphere Programme (IGBP)

The literature on these projects is widely circulated to the scientific community. The major inputs to these large scale experiments are likely to come from satellites. In India, several institutes have taken up some of these activities, but not with enthusiam that it deserves.

Future Outlook

Looking at the major efforts undertaken by various countries notably among them, NASA, ESA, Japan, Germany, and to a modest scale by China & India, the future of application technology from space appears to be encouraging in monitoring our earth's environments. ISRO's new initiative to define an ocean satellite system in response to the Department of Ocean Development requirements is a positive step in meeting the data requirements of the specific scientific community. New instruments need to be developed taking advantage of fast progressing technology of microwave and laser systems. Optical, thermal

and microwave sensors are all needed to observe different variables of the earth surface which will eventually converge in synergisms in future operational systems. The mass of data available is of itself a major focal point of the data management problem for remotely sensed data from satellites. Finally, the challenge lies in 'assimilating' these data from various sources into numerical models for prediction.

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